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Reflected-starlight phase curves: an observing strategy to constrain the radius and atmospheric properties of directly imaged exoplanets

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Abstract

The Nancy Grace Roman Space Telescope, to be launched in 2025, will directly image exoplanets in reflected starlight for the first time. This observing technique will enable the study of a population of exoplanets whose atmospheres cannot be characterized with current techniques. Previous works have analysed the possible science outcome of reflected-starlight observations through atmospheric retrievals. These have shown that an accurate atmospheric characterization from a reflected-light spectrum will likely be hindered if the radius and the atmospheric properties (e.g. cloud properties) of the exoplanet are unknown a priori. In this work we study how different observing strategies can improve the atmospheric characterization in such cases. We conclude that combining measurements at different star-planet-observer phase angles (α) is a powerful strategy to better characterize the atmosphere of an exoplanet and constrain its radius.

Introduction

Understanding how planetary and atmospheric properties affect the reflected-starlight spectra of exoplanets is a key to interpreting future direct-imaging observations. This may also help propose observing strategies to optimize the prospects for characterization of the planet. That understanding of the physical fundamentals of exoplanet remote sensing will be applicable to space missions such as the Roman Telescope, LUVOIR or HabEx.

Model and retrieval procedure

We assume a H_2-He atmosphere with methane as the only absorbing species and a cloud layer. The atmospheric parameters that we consider in our model are: the methane abundance (f_{CH4}), the optical thickness of the cloud (τ_c), the altitude at which the cloud top is located, the geometrical extension of the cloud, the single-scattering albedo (ω_0) of the aerosols and their effective radius (r_{eff}). We also include the planet radius (R_p) as another model parameter. Through Mie theory, r_{eff} determines the aerosol scattering phase function which describes the interaction between the photons and the aerosols depending on the incident direction of the light.

For a grid of ~300,000 atmospheric configurations, we computed their reflected-starlight spectra (500-900 nm) at phase angles α=37º, 85º and 123º by means of a pre-existing multiple-scattering radiative transfer code[1]. The spectral resolution is R~125-225, consistent with mission concepts like LUVOIR or HabEx. We simulated observations of three atmospheric configurations, labelled as cloud-free, thin-cloud and thick-cloud scenarios. These observations were simulated at each of the three phase angles considered by adding wavelength-independent noise. The signal-to-noise ratio was set to S/N=10 in all cases.

We used the MCMC retrieval method developed in Carrión-González et al. (2020)[2] to run atmospheric retrievals for each of the single-phase simulated observations at α=37º, 85º and 123º. For that, we assumed no prior knowledge of any of the model parameters. Furthermore, we extended this retrieval method in order to run simultaneous retrievals of multiple observations at different phase angles.

Results

We first ran single-phase retrievals (Fig. 1) at each phase angle and repeated this for the three cloud scenarios. We verify that no single-phase observation with S/N=10 allows us to distinguish between cloudy and cloud-free atmospheres. This is due to the parameter correlations between R_p, the cloud properties and the methane abundance. This consistent with the findings in Carrión-González et al. (2020) for α=0º. We also find that a single-phase observation at a large phase angle (123º) can constrain the planet radius with an error smaller than 35% in all of the cloud scenarios. Our findings are consistent with previous works carrying out single-phase retrievals of reflected-starlight spectra[3].

We also ran multi-phase retrievals to combine spectra obtained at different phase angles. We tested the combinations 37º+85º, 37+123º and 37º+85º+123º. For comparison, we also ran single-phase retrievals at α=37º with an increased signal-to-noise ratio of S/N=20. The adopted phase angles are within the ranges of observable conditions for the known exoplanets that will be detectable by LUVOIR and HabEx. Such ranges of α might also be observable for certain targets in an optimistic configuration of the Roman Telescope coronagraph[4].

We find that combining small (37º) and large (123º) phase angles is an effective strategy to break some of the aforementioned correlations between model parameters (Fig. 1). Both of the combinations (37+123º) and (37º+85º+123º) allow to distinguish between cloudy and cloud-free atmospheres in all cloud scenarios and accurately constrain most of the model parameters. Combining small (37º) and moderate (85º) phase angles fails to achieve this. Similarly, a single-phase retrieval at α=37º with S/N=20 also fails to break the parameter correlations.

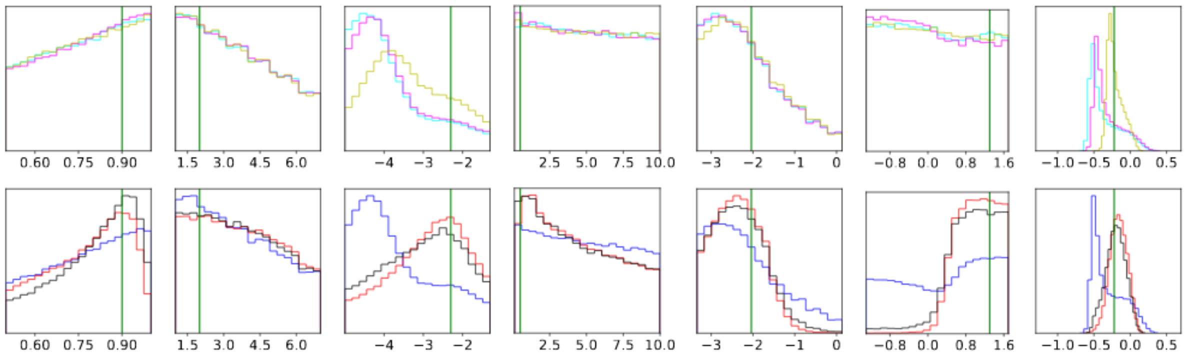

Fig. 1. Marginalized posterior probability distributions of each model parameter for different retrieval exercises. Top row: single-phase retrievals for the thick-cloud scenario at phase angles 37° (cyan), 85° (magenta) and 123° (yellow). Bottom row: multi-phase retrievals for the thick-cloud scenario. Blue lines mark the combination (37°+85°); red lines, (37°+123°) and black lines, (37°+85°+123°). No prior knowledge on the cloud properties or the planet radius was assumed in these retrievals.

The shape of the aerosol scattering phase function is found to affect the improvements in multi-phase retrievals. We verified that the improvements are smaller for more isotropic scattering phase functions. The cloud properties and their uncertainties hence play an important role in the retrievals. Indeed, we find that if the cloud properties are assumed known a priori, the retrieval results become overly optimistic. This is consistent with previous works adopting such assumptions[5] and happens because less correlations between model parameters take place in the retrievals.

We therefore conclude that combining small and large phase angles is a generally effective observing strategy to accurately characterize exoplanets for which no prior information on the planet radius or cloud composition is available. This suggests that exoplanets with wide ranges of observable phase angles should be priority targets for reflected-starlight telescopes.

References

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